Les ondes gravitationnelles
à portée de main

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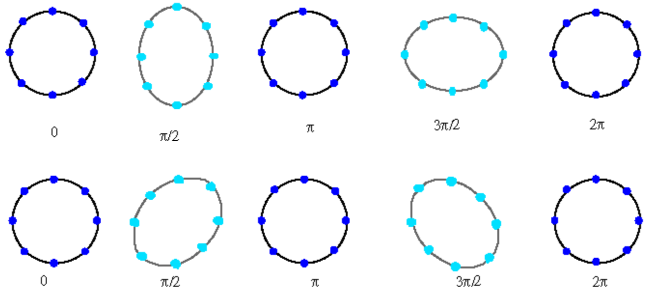
Séminaire au LPC
15 mars 2013

Gravitational waves

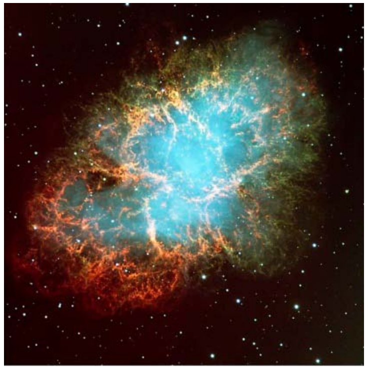
- General Relativity prediction
  - Space-time strain propagating at speed of light
  - Transverse, quadrupolar, two polarizations

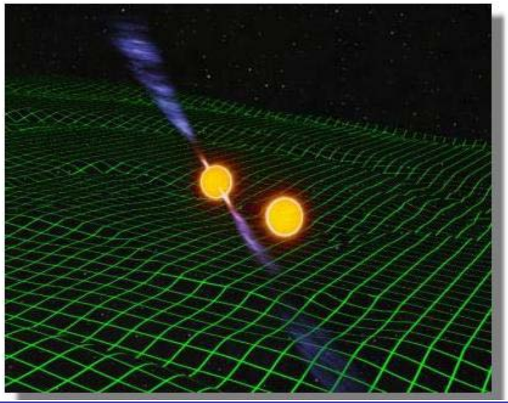


- GW luminosity $= \frac{c^5}{G} \; \epsilon^2 \; \left(\frac{R_S}{R}\right)^2 \; \left(\frac{v}{c}\right)^6$

asymmetric compact relativistic

➔ Astrophysical sources





Gravitational waves as a probe

Gravitation

Sources

Universe

- GW generated by powerful mass acceleration
  - Very energetic events in the Universe
  - GW probe event dynamics

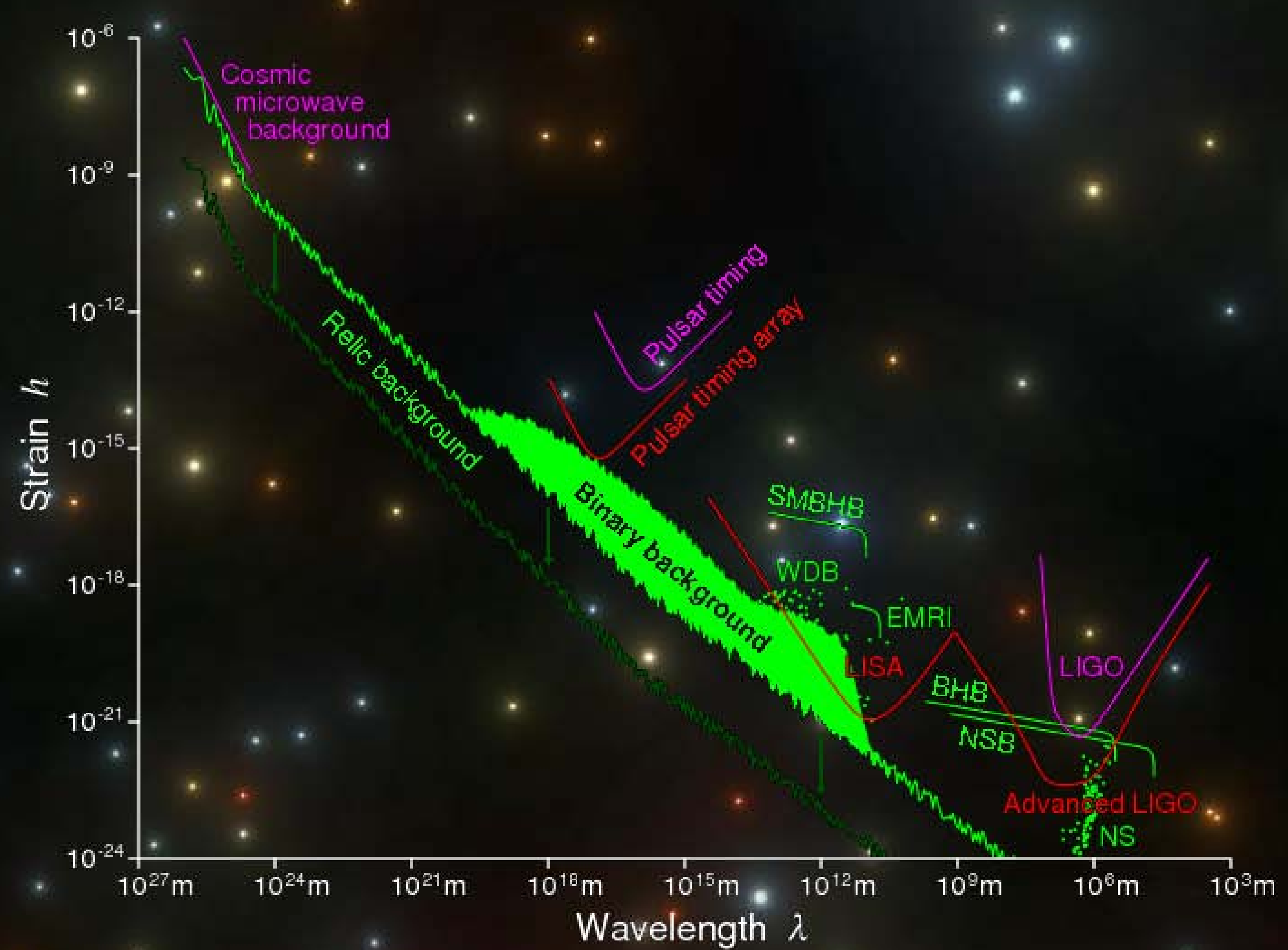
- Gravitation is the only clue to 96% of matter in the Universe
  - GW probe gravitation in new regime

General Relativity

Astrophysics

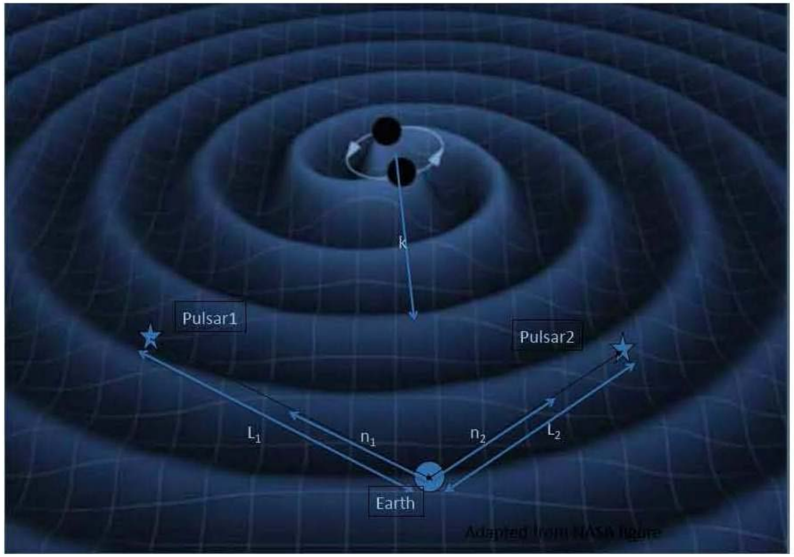
Cosmology

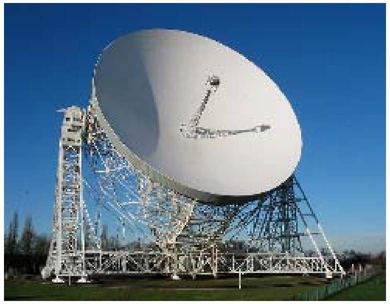
Gravitational wave spectrum



Pulsar timing arrays

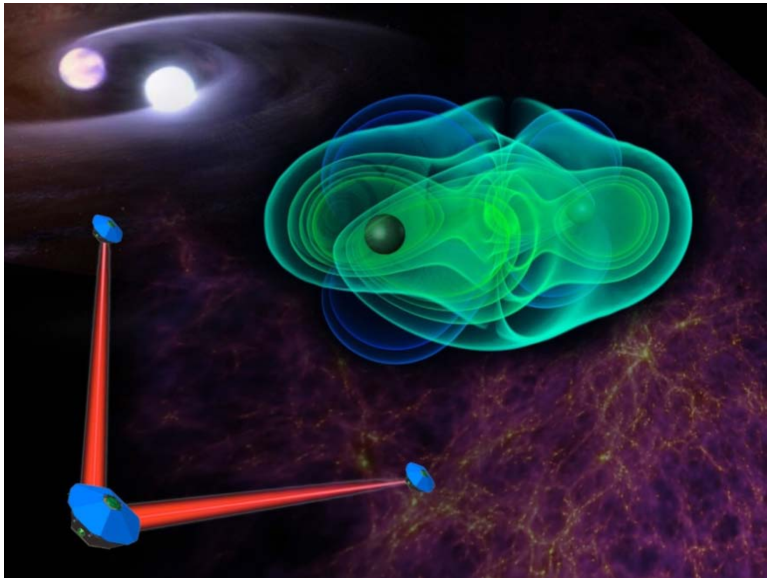
- A galactic scale detector
  - Pulsars = cosmic clocks
  - nano-Hz band
- Probe stochastic background of super-massive black hole binaries
  - Upper limits for past 20 years
  - Ruled out SMBH binary in 3C66B





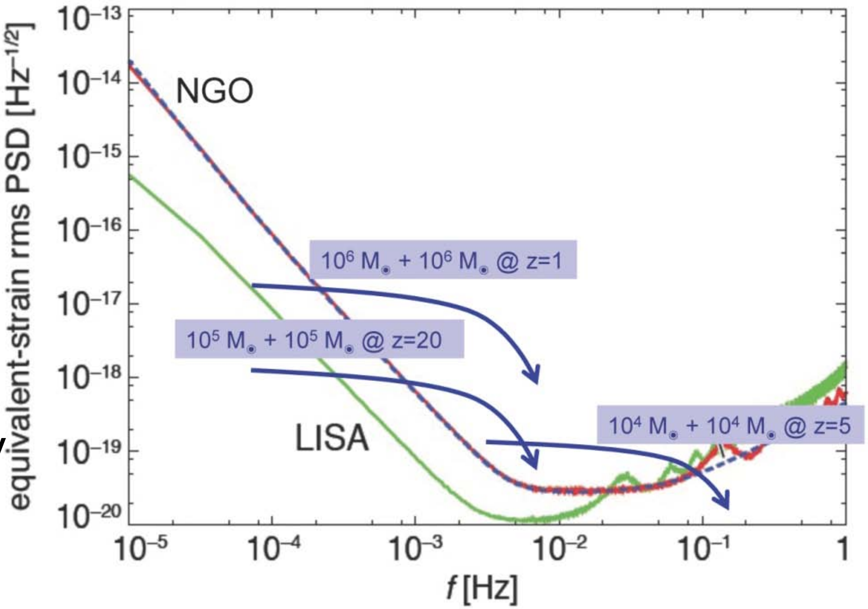
- Goal : weekly observations of ~20 millisecond pulsars over 5 - 10 years with TOA precisions of ~100 ns
  - International Pulsar Timing array

eLISA-NGO

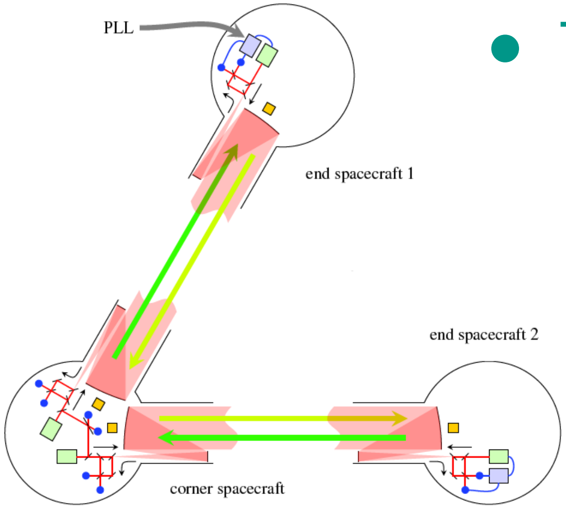


- European avatar of the LISA project
  - Reduced size and bandwidth
  - Will apply for L2 mission selection in ESA Cosmic Vision program
    - » Launch ~2028

- Guaranteed sources, rich science program
  - Super-massive black holes and large structure formation
  - White-dwarf binary systems in the Galaxy
  - Cosmology, ultra-strong gravity tests

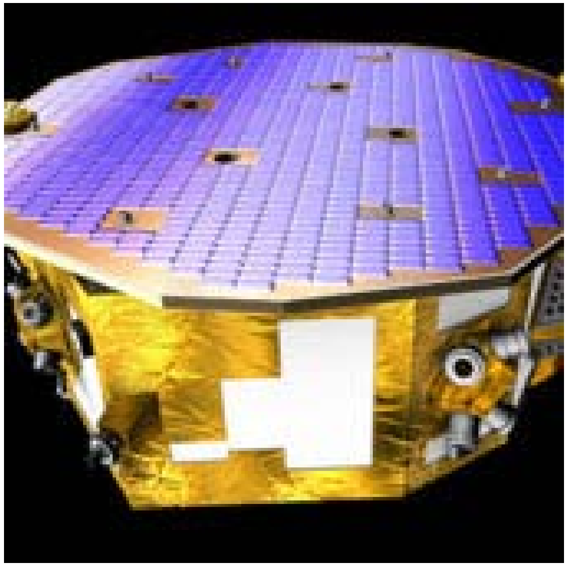


LISA Pathfinder



- Technical challenges
  - eLISA-NGO = constellation of 3 satellites, 2 arms
  - Drag-free control
    - » Control satellites around free-falling masses
  - Laser interferometry to measure distances between test masses
    - » ~10 pm over 10^6 km

- LISA Pathfinder: technology demonstrator
  - Inertial sensors, thrusters
  - Laser interferometry, at same accuracy level as eLISA-NGO
  - Will be launched in 2015



Ground based interferometric detectors:

Past and future

Ground-based interferomters

- 1st generation interferometric detectors
  - ◆ Initial LIGO, Virgo, GEO600

Unlikely detection

Science data taking
First rate upper limits
Set up network observation

  - ◆ Enhanced LIGO, Virgo+

VOUS ÊTES ICI

Improved sensitivity

Lay ground for multi-messenger astronomy

- 2nd generation detectors
  - ◆ Advanced LIGO, Advanced Virgo, GEO-HF, KAGRA

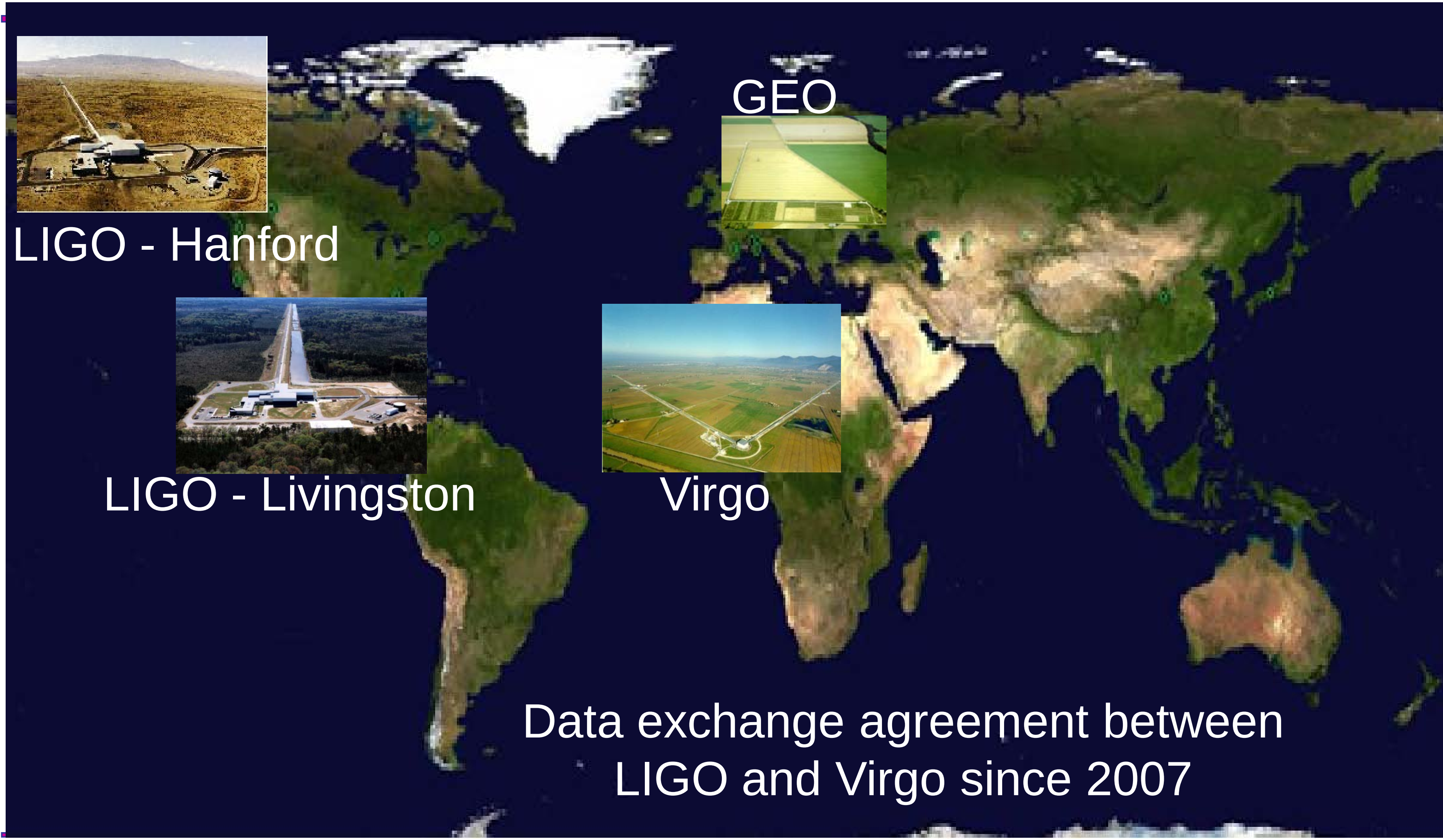
Likely detection

Routine observation
➔ GW astronomy

Thorough observation of Universe with GW

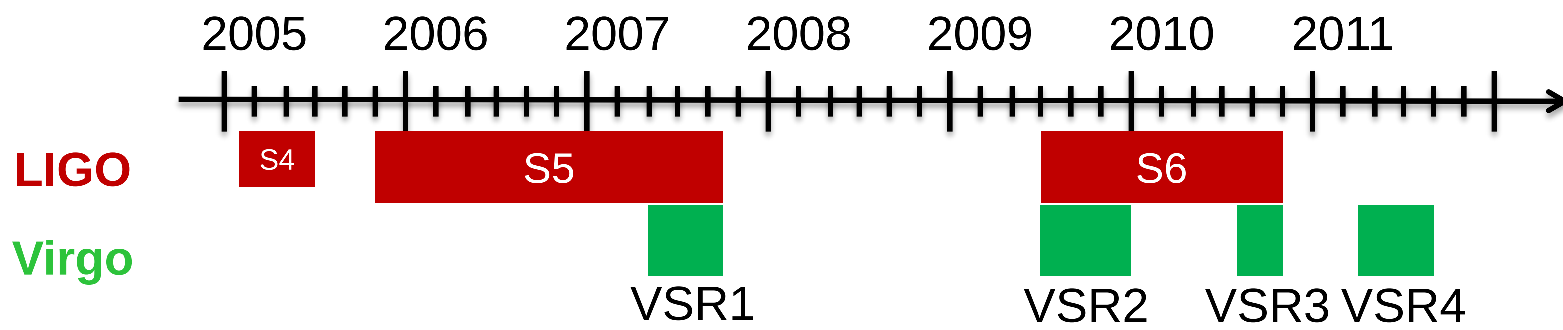
- 3rd generation detectors
  - ◆ Einstein Telescope, US counterpart to ET

1^{st} generation (I)

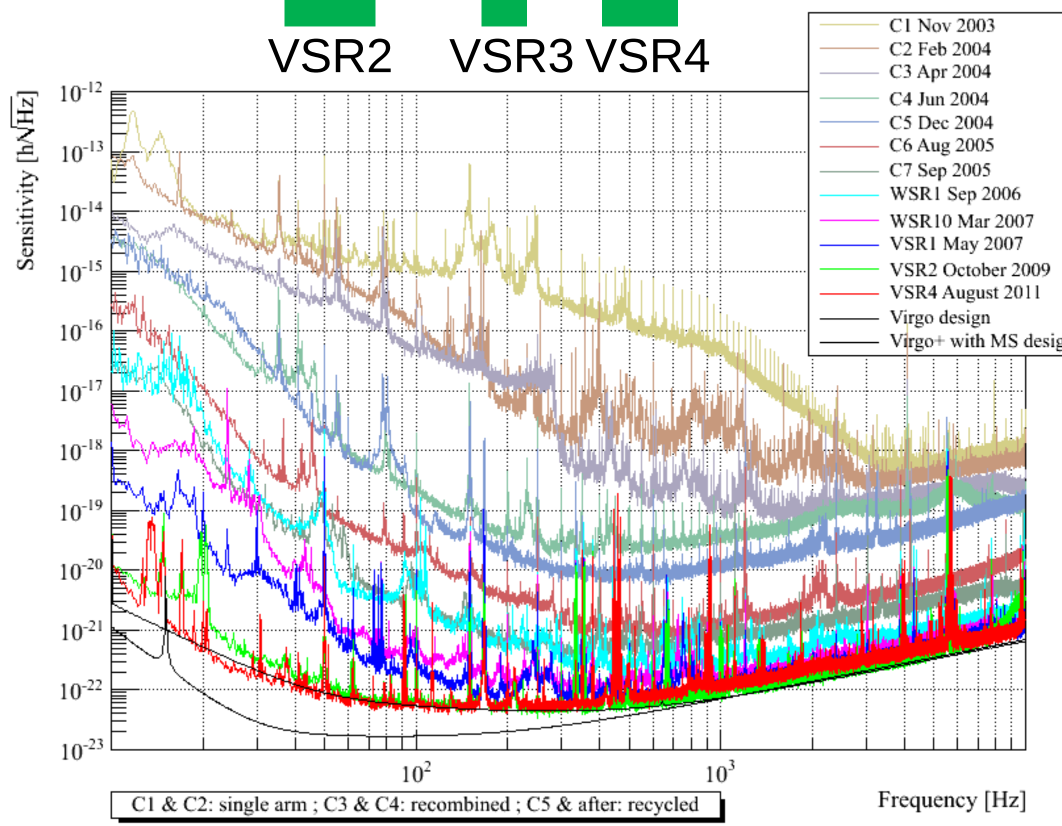


Data exchange agreement between LIGO and Virgo since 2007

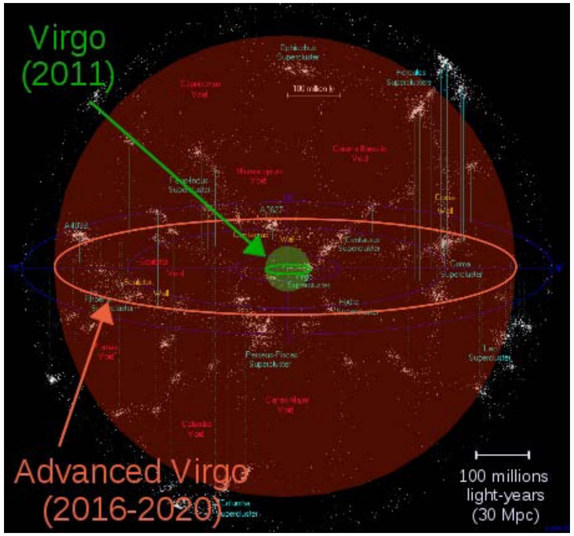
1st generation (II)



- Operating detectors at their nominal sensitivities took years of effort
- Long science data taking
- No detection, but some science!
  - More later…

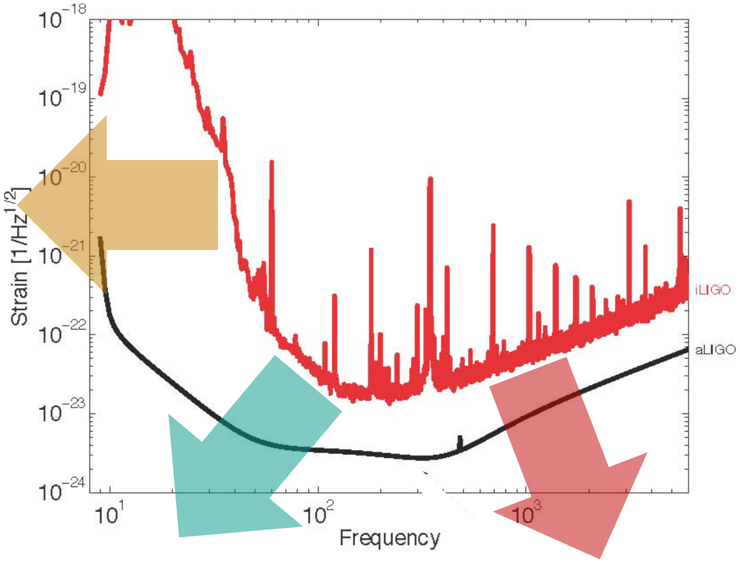


2^{nd} generation (I)



Seismic noise
Improved seismic isolation

More later about technical challenges…



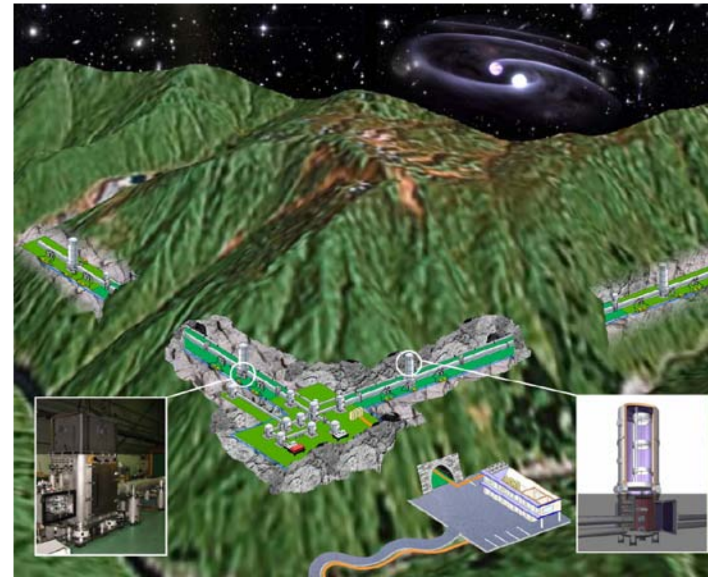
x10 distance
x1000 volume
More in a day of observation than in a year…

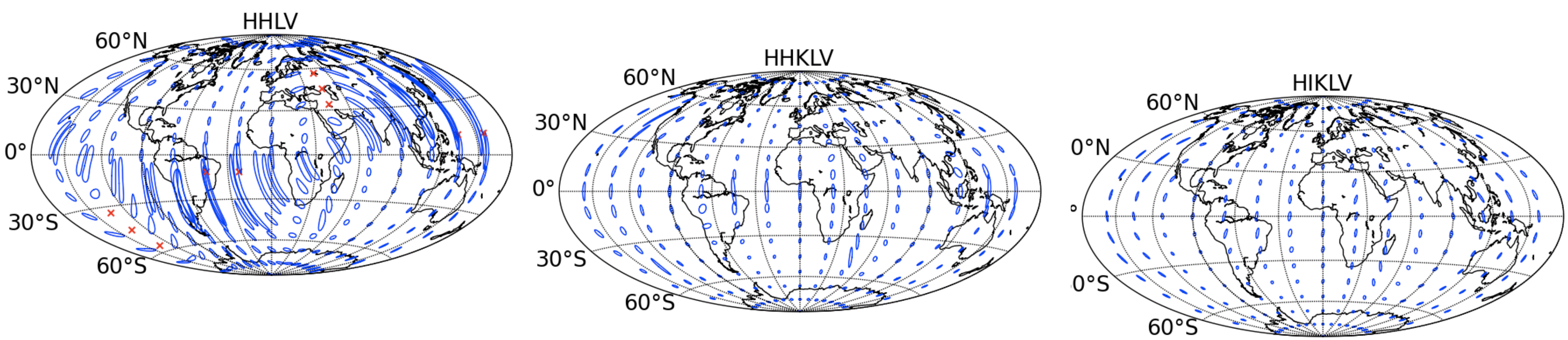
Thermal noise
Monolithic suspensions
Improved mirror coatings
Larger beam size

Quantum noise
Higher laser power
Thermal compensation
Signal recycling
DC detection

2nd generation (II)

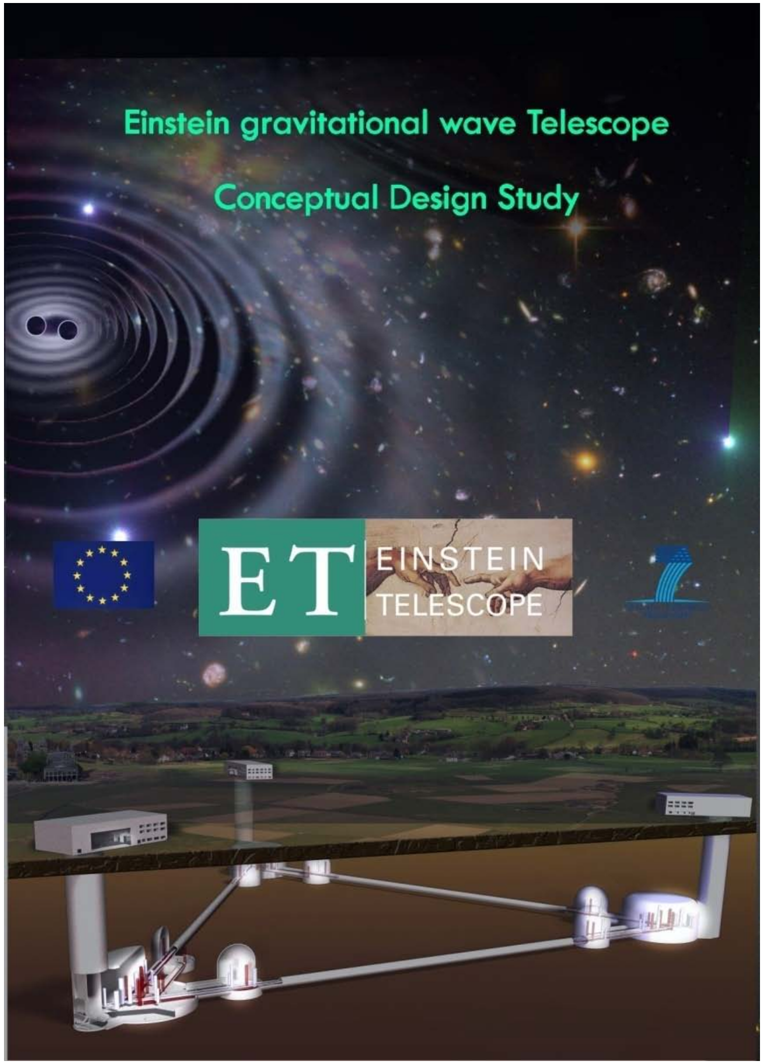
- Toward an extended detector network
  - KAGRA in Japan
  - Third LIGO detector probably located in India
  - Duty cycle
    - » ~80% at best for one detector
    - » ~50% for three detectors in coincidence
  - Sky coverage
  - Source localization capability





3rd generation

- Sensitivity
  - 10x better than 2nd generation
  - Bandwidth starting at 1 Hz
  - BNS / BBH to z ~ 4 / 10
- Configuration
  - Several large interferometers (30km?)
  - Underground
- Improved technologies
  - Cryogenic, mirrors, laser, squeezing…
- Status
  - ASPERA roadmap
  - FP7 Design Study
    - » 2008-2011
  - Construction?
    - » Probably not before 1st detection



From first generation to second generation ground based interferometric detectors:

Science within reach

A variety of GW searches

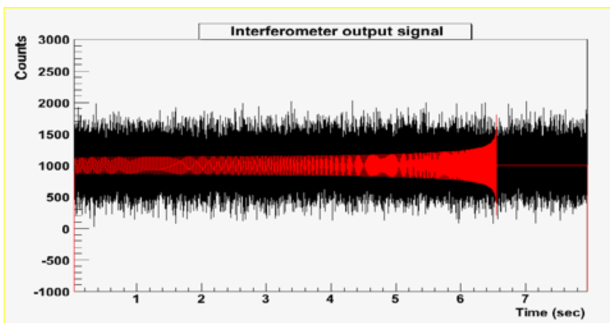
- All sky searches
  - Compact coalescing binaries
  - Burst sources
    - Supernovae, cosmic strings…
  - Continuous waves (spinning neutron stars)
  - Stochastic background
- Targeted searches
  - Known pulsars
  - Neutron star oscillations
    - SGR flares, pulsar glitches
  - Gamma ray bursts
    - Long & short
  - High energy neutrinos
- Search for electromagnetic counterparts to GW

Gravitational waves

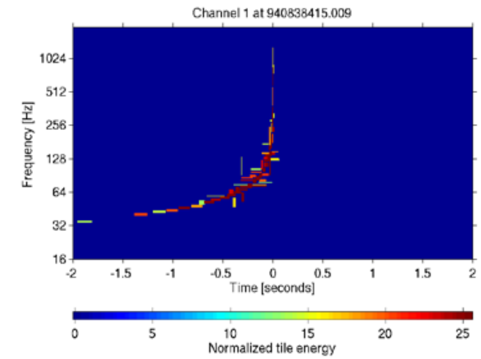
Other messengers

Transient data analysis in a nutshell

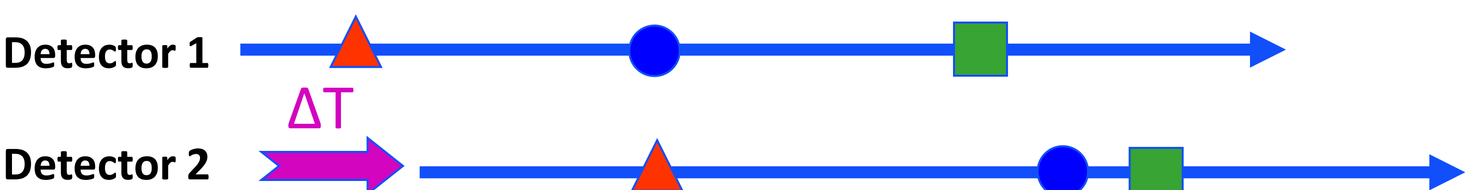
- The data are a stream of noise in which the burst and CBC searches try to identify rare and weak events
  - The noise is not Gaussian (“glitchy” detectors/environment) and not stationary
- Template searches for modeled signals



- Excess power searches for un-modeled signals



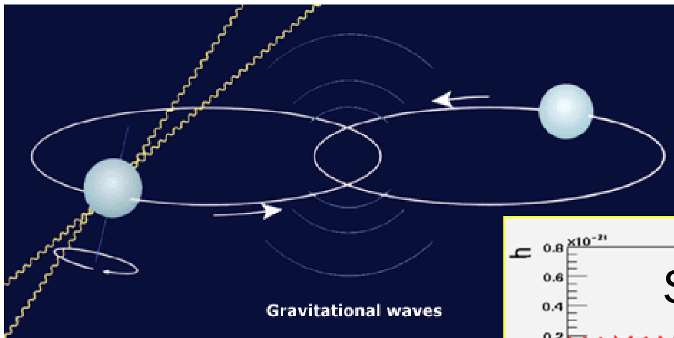
- Coincidences are our most powerful tool
  - Reduced false alarm rate
  - Background can be estimated by applying time offsets between detectors



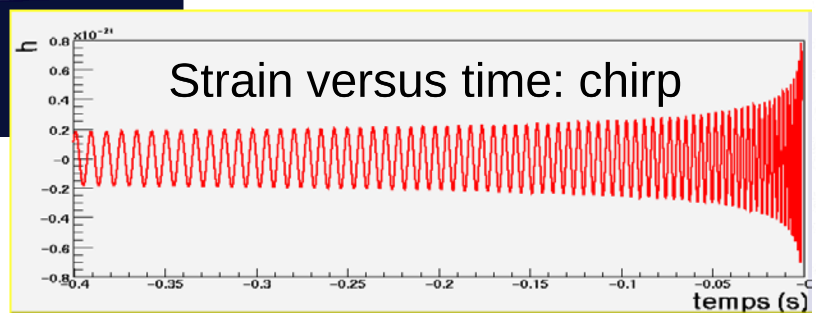
+ data quality characterization & vetoes

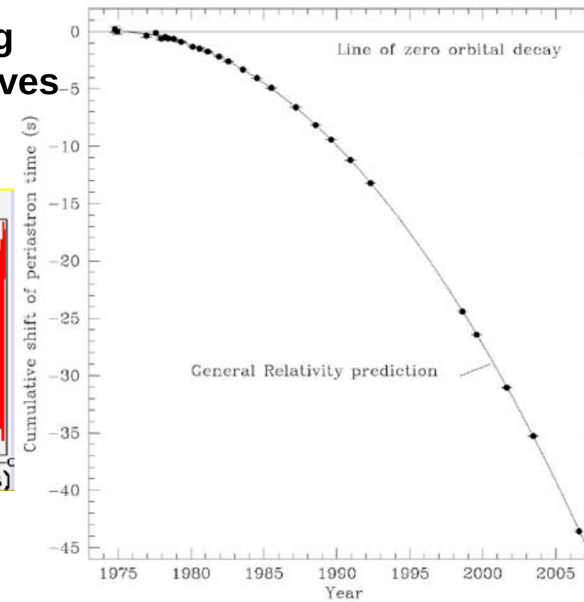
Compact binary coalescences

- Final evolution stage of compact binary systems
  - Systems like PSR1913+16 reaching coalescence of the two stars



Orbit decays by radiating energy as Gravitational Waves



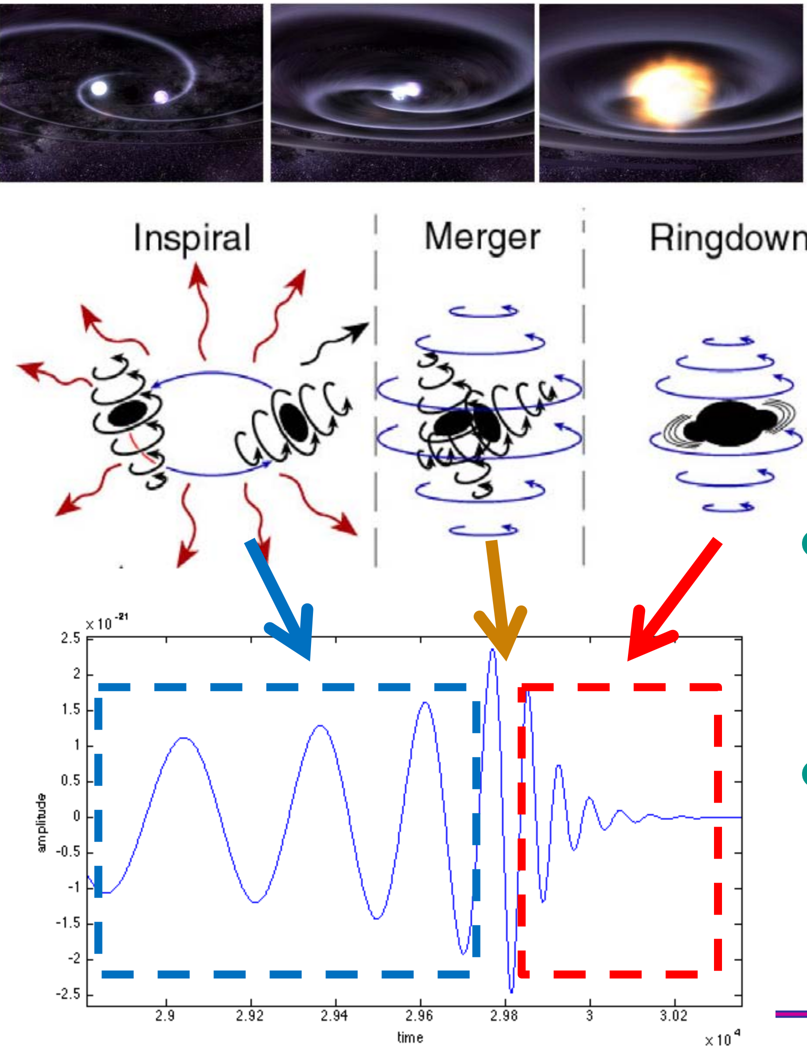


- System may involve
  - Neutron stars (NS)
  - Black holes (BH)
    - » For ground based detectors, stellar mass black holes
    - » Advanced detectors: up to intermediate mass black holes
    - » Super-massive BH: lower frequency, space based detectors, pulsar timing

Chirp ends at frequency inversely proportional to total mass

$$f_{\mathrm{ISCO}} = \frac{2.8 M_{\odot}}{M}\ 1600\ \mathrm{Hz}$$

Phases of CBC evolution



- **Inspiral**
  - The realm of post-Newtonian expansions
  - Accurate analytical computations
    - » adiabatic evolution of quasi-circular orbit
  - Valid up to innermost stable circular orbit

$$f_{\mathrm{ISCO}} = \frac{2.8 M_{\odot}}{M}\ 1600\ \mathrm{Hz}$$

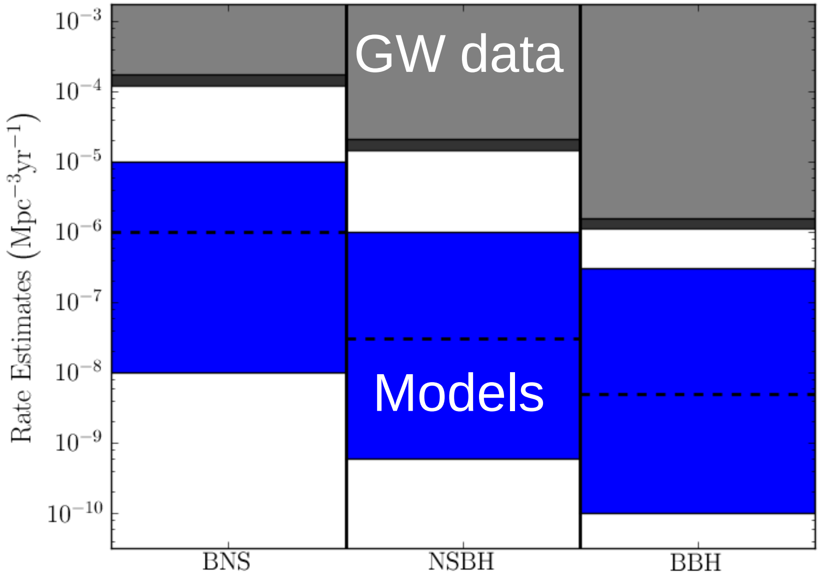
  - $\mathrm{Length} \sim 34\ \left(\frac{\mathcal{M}}{M_{\odot}}\right)^{-5/3}\left(\frac{f_0}{40\ \mathrm{Hz}}\right)^{-8/3}\ \mathrm{s}$
- **Plunge/Merger**
  - The realm of numerical relativity
  - Duration << 1 s
- **Ringdown**
  - The realm of black hole perturbation theory
  - Relaxation of perturbed final black hole
  - Duration << 1 s

CBC: estimating the rates

- Uncertain, even for most confident predictions
- BNS
  - Extrapolations from observed Galactic binary pulsars
    - Small sample, few parameters
  - From population-synthesis models
    - Observational and theoretical constraints on parameters
- NS-BH and BBH
  - From population-synthesis models
    - Many open questions for BBH
  - From extra-Galactic X-ray binaries
    - IC10 X-1 and NGC300 X-1
    - Formed by a 20-30 black hole and a massive Wolf-Rayet star
    - Should evolve into a binary black hole with Mchirp~15 $M_{\odot}$
- Still an open point whether BNS or BBH dominate

CBC: initial detector rates

IFO	Source[a]	$N_{\rm low}$ $\rm yr^{-1}$	$N_{\rm re}$ $\rm yr^{-1}$	$N_{\rm pl}$ $\rm yr^{-1}$	$N_{\rm up}$ $\rm yr^{-1}$
	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
Initial	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			< 0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]



- Rate upper limits from LIGO-S6/Virgo-VSR2-3 data
- ~1 order of magnitude above optimistic estimates

CBC: advanced detector rates

IFO	Source[a]	$\dot{N}_{\mathrm{low}}$ yr^{-1}	$\dot{N}_{\mathrm{re}}$ yr^{-1}	$\dot{N}_{\mathrm{pl}}$ yr^{-1}	$\dot{N}_{\mathrm{up}}$ yr^{-1}
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^{b}	300^{c}
	IMBH-IMBH			0.1^{d}	1^{e}

Realistic rates do get substantial for advanced detectors

BBH visible up to 1 Gpc

Science with GW from compact binaries

- General Relativity
  - Test theory in strong field
  - Test/constrain alternative gravity theories
- Astrophysics
  - Measure merger rates
    - As a function of parameters
  - Inform source distribution
    - Masses, spins, spatial distribution
  - Study effect of matter in BNS waveform
  - Short, hard GRBs
    - Confirm or rule out merger progenitor
- Cosmology
  - CBC inspirals as standard sirens
    - Independent measurement of Hubble constant

Challenges

➔ Sensitivity

➔ Waveforms

Known, but large parameter space, not fully explored yet

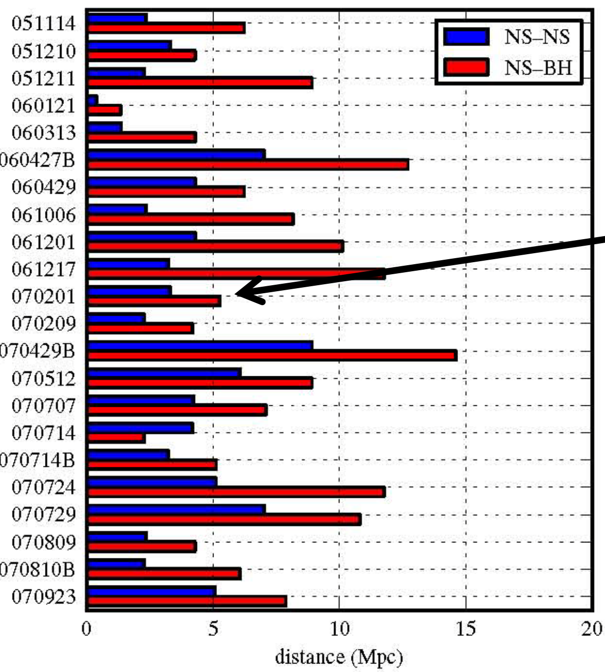
➔ Multi-messenger astronomy

Many of the science goals require combining information from GW, electromagnetic and/or particle observations.

GRB-triggered CBC searches

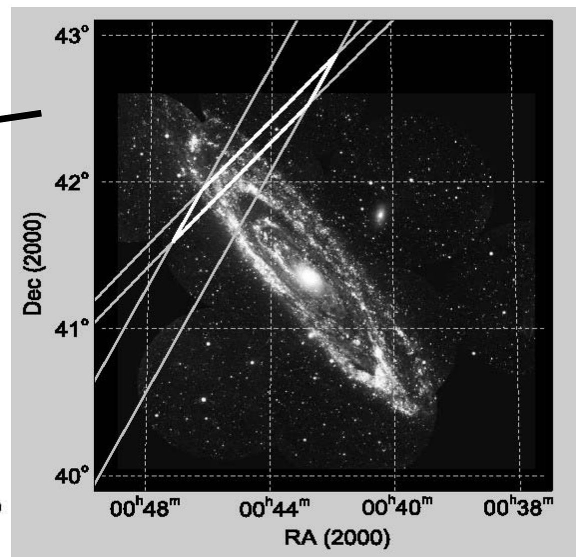
- No detection so far, distance lower limits derived

S5-VSR1



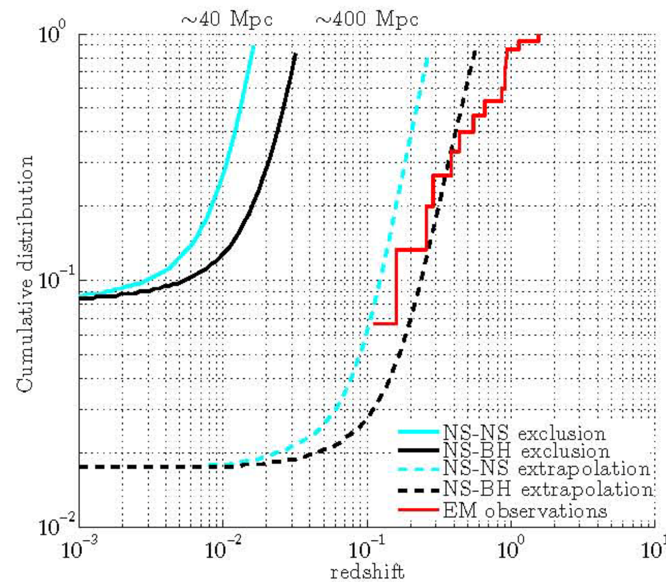
The interesting case of GRB 070201

Not a merger in M31



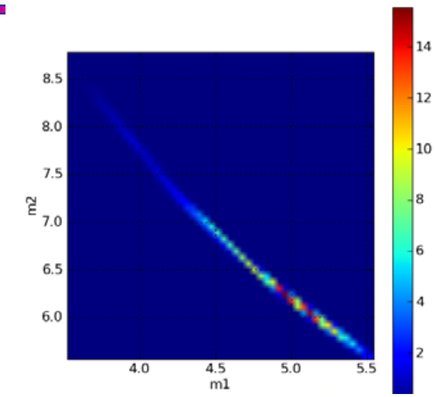
IPN 3σ Sky Localization
Mazets et al, ApJ 2008

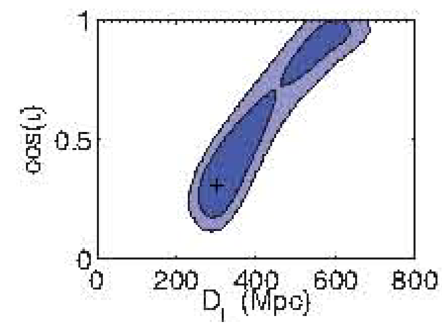
S6-VSR2/VSR3

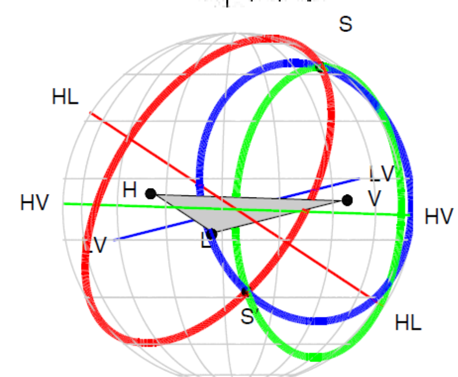


CBC parameter estimation

- Using CBC GW sources for astrophysics or cosmology requires measuring source parameters
- Degeneracies among intrinsic parameters and among extrinsic parameters
- Individual component masses not well measured
  - Some combination of masses – *chirp mass* – accurately measured
    - » Drives phase evolution at leading order, mass ratio enters at higher orders
    - » Mass – spin degeneracy
    - » Waveform uncertainties
- Distance
  - Distance – inclination degeneracy
- Sky location
  - Primarily from time of flights across detectors
- An electromagnetic counterpart would help pinpoint location, lift some of the degeneracies, provide redshift



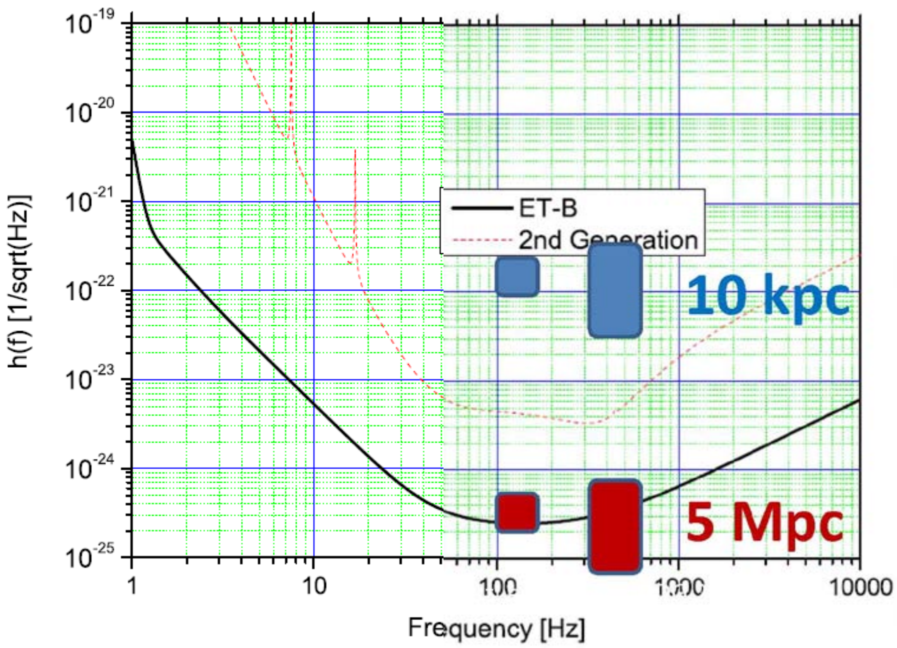




Burst GW: supernovae

- Galactic rate of core-collapse SN ~1 per 30-50 years
  - Within reach of 2nd generation detectors, but rare
  - (Lack of) detection will constrain SN mechanisms
- Expect 1 within 5 Mpc every 2-5 years
  - Needs 3rd generation detectors

Sensitivity estimated with Dimmelmaier et al. waveforms (bounce mechanism)



Continuous waves: initial detectors

GW upper limits beating spin-down limit for two pulsars

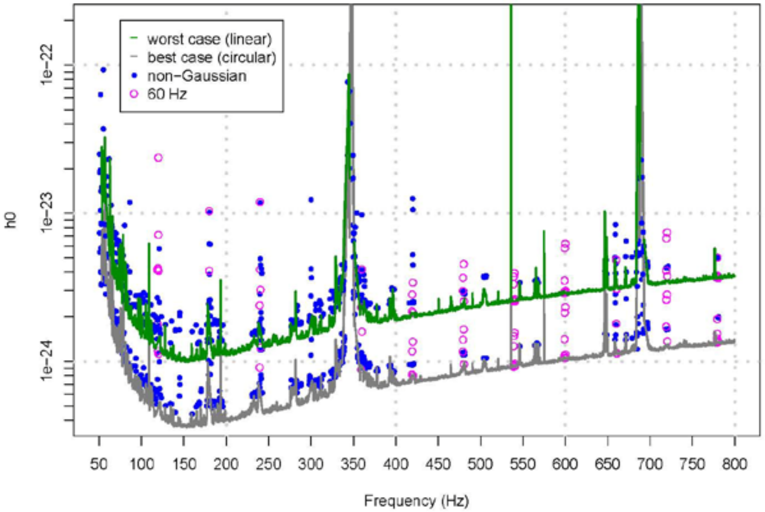
- Crab @ ~60 Hz (LIGO data)
  - » GW energy < 2% of spin-down energy
  - » $\varepsilon < 1.3\times10^{-4}$
- Vela @ ~22 Hz (Virgo data)
  - » GW energy < 35% of spin-down energy
  - » $\varepsilon < 1.1\times10^{-3}$

Other targeted searches

- 116 known millisecond and young pulsars with LIGO S5 data
  - » Best h limit 2.3×10^{-26}
    - » J1603−7202, 135 Hz
  - » Best ε limit 7.0×10^{-8}
    - » J2124−3358, 406 Hz, 0.2 kpc

All-sky searches

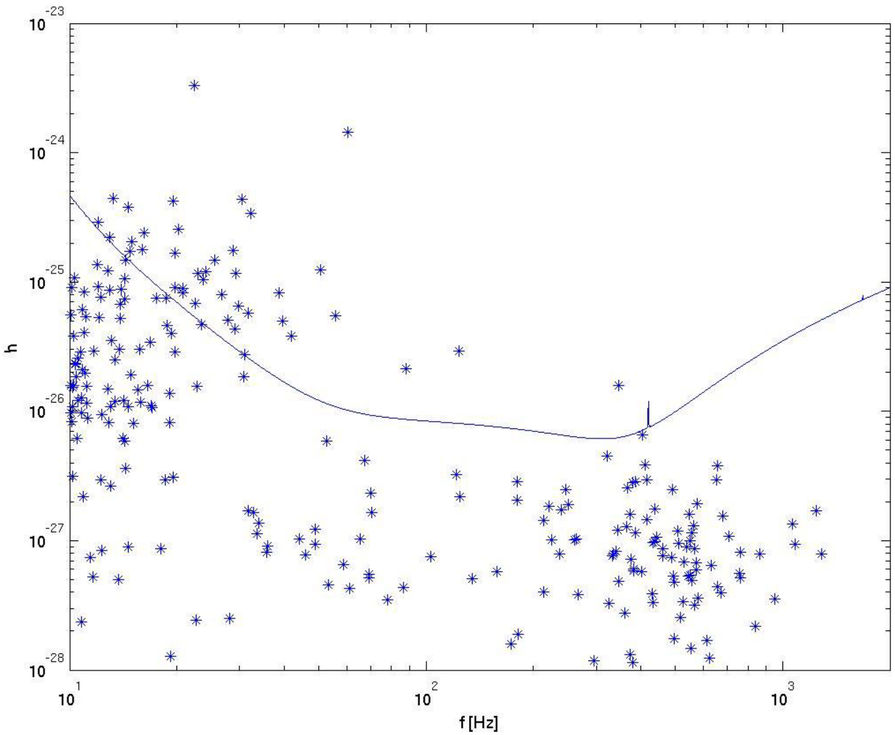
- S5 LIGO data
- At high frequency, sensitive to $\varepsilon = 10^{-6}$ up to ~500 pc

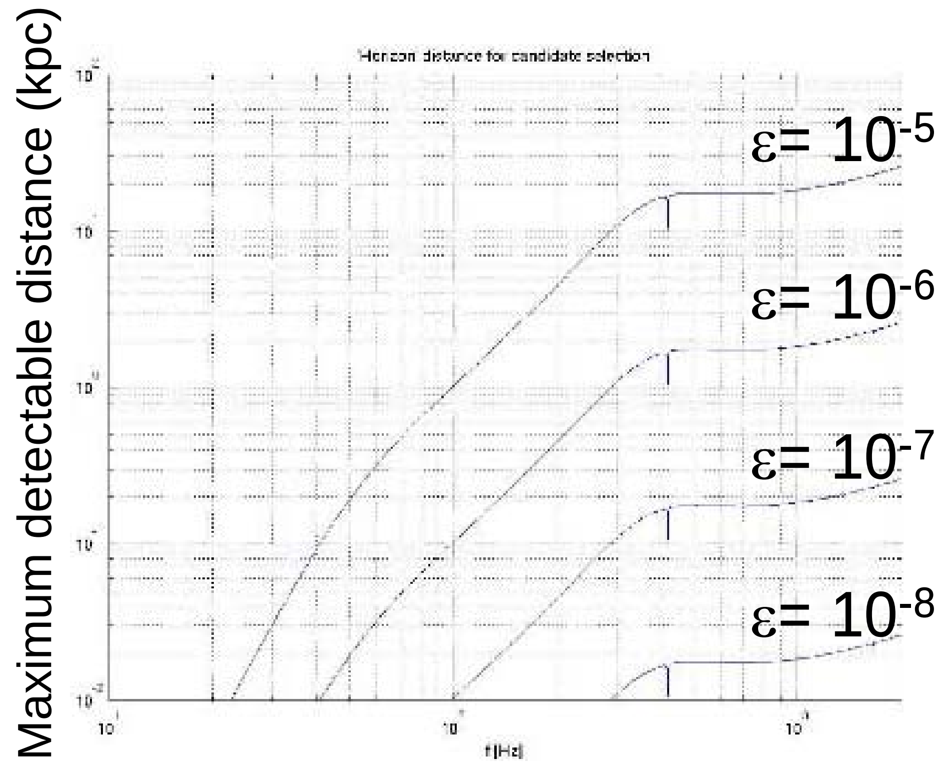


Continuous waves: advanced detectors

Minimum detectable amplitude with 1yr observation of Advanced Virgo, compared to spin-down limits of known pulsars

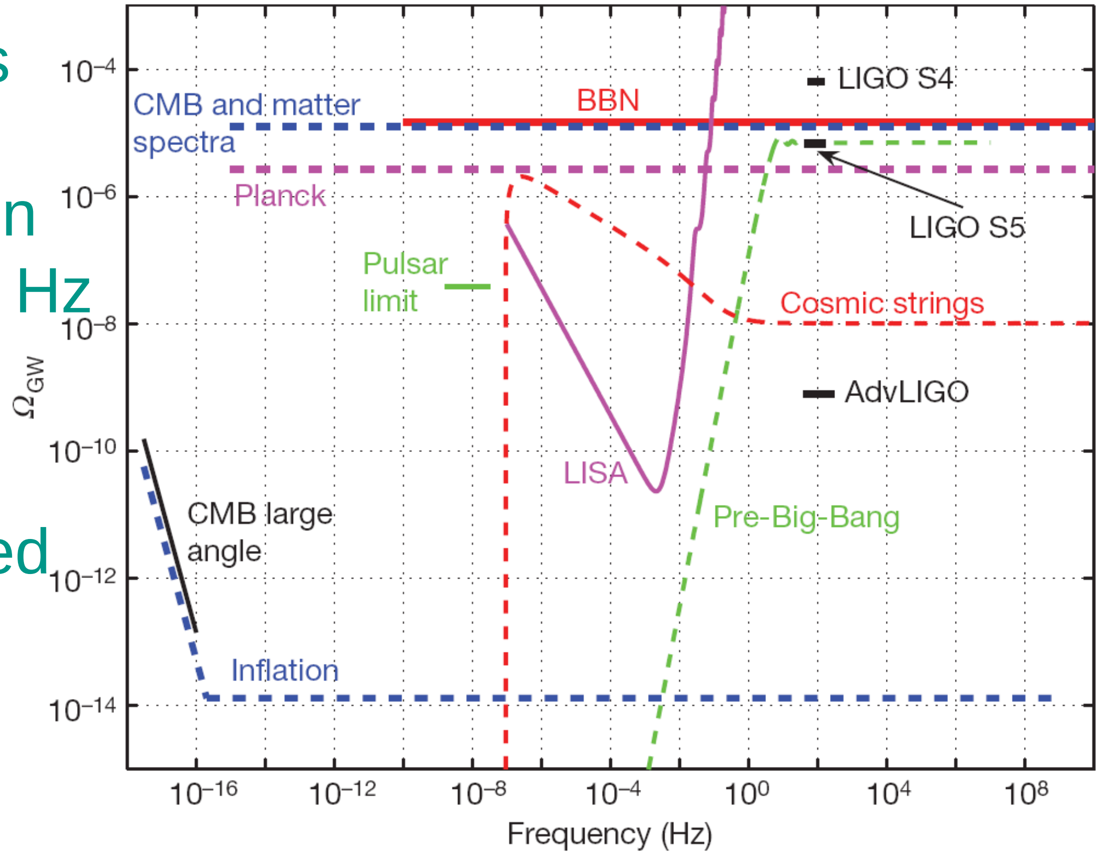
Significant fraction of the Galaxy probed for large ellipticities





Cosmological stochastic background

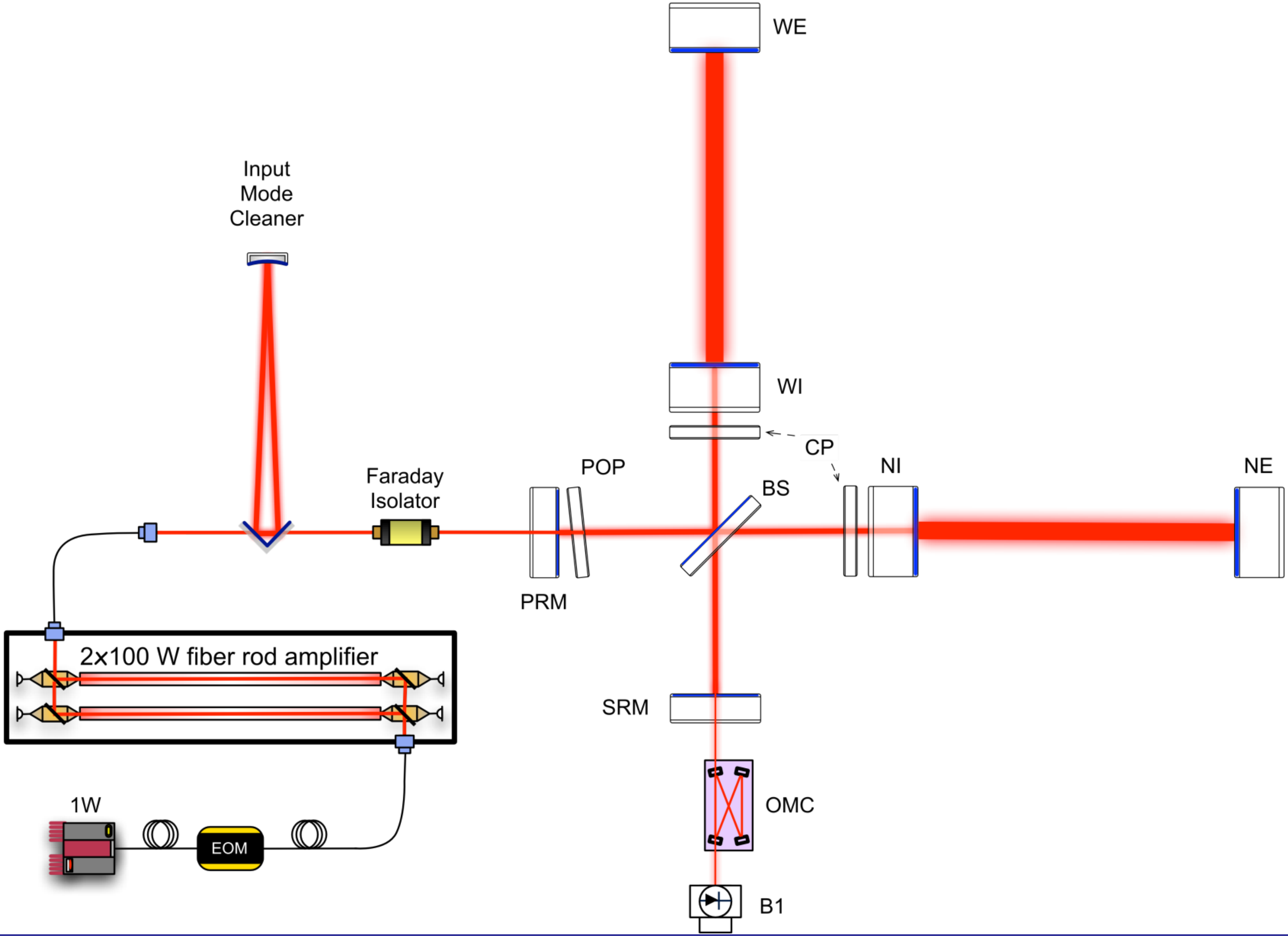
- Big Bang Nucleosynthesis upper limit on GW energy density $\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$ beaten with LIGO S5 data @ 100 Hz
- Some models partially excluded
- More models will be probed with advanced detectors



From first generation to second generation ground based interferometric detectors:

Experimental challenges

Advanced Virgo optical scheme



Laser

Initial detectors
~10 W input power

Enhanced detectors
~50 W

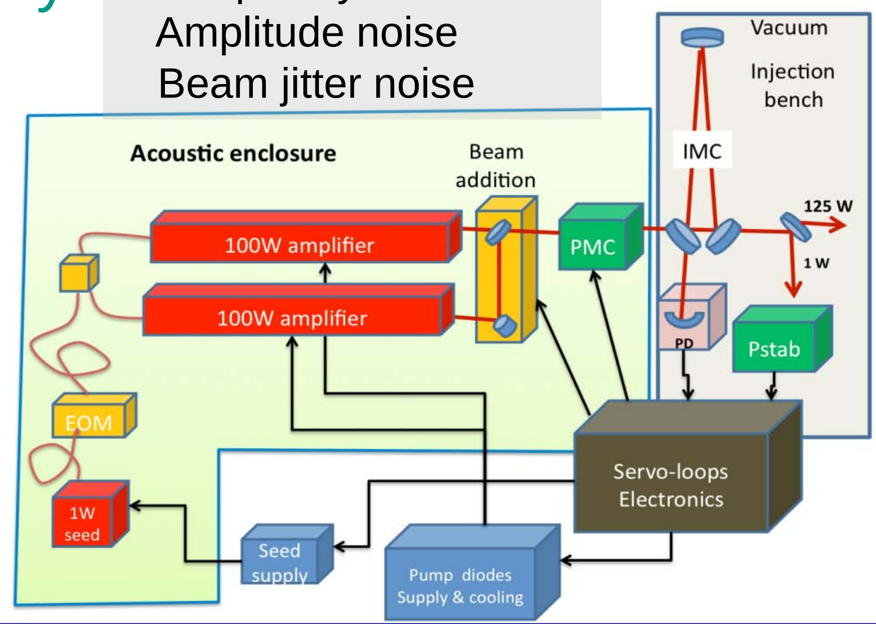
Advanced detectors
~200 W

- Reduce shot noise

➔ Improve high frequency sensitivity

- Cope with high power
  - Radiation pressure noise
  - Mirror thermal lensing
  - High power through input optics
- Requires new developments
  - Heavier mirrors
  - Improved thermal compensation
  - High power, low noise, input optics

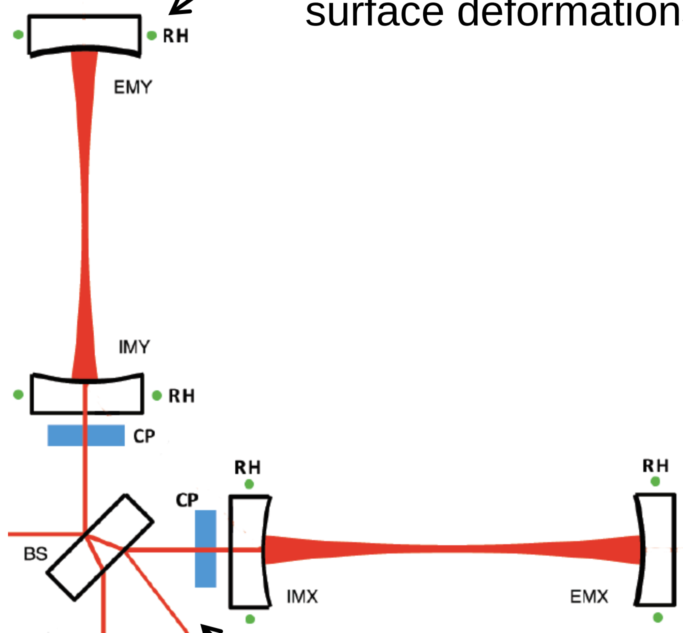
Other requirements
- Beam quality
- Frequency noise
- Amplitude noise
- Beam jitter noise



Thermal compensation

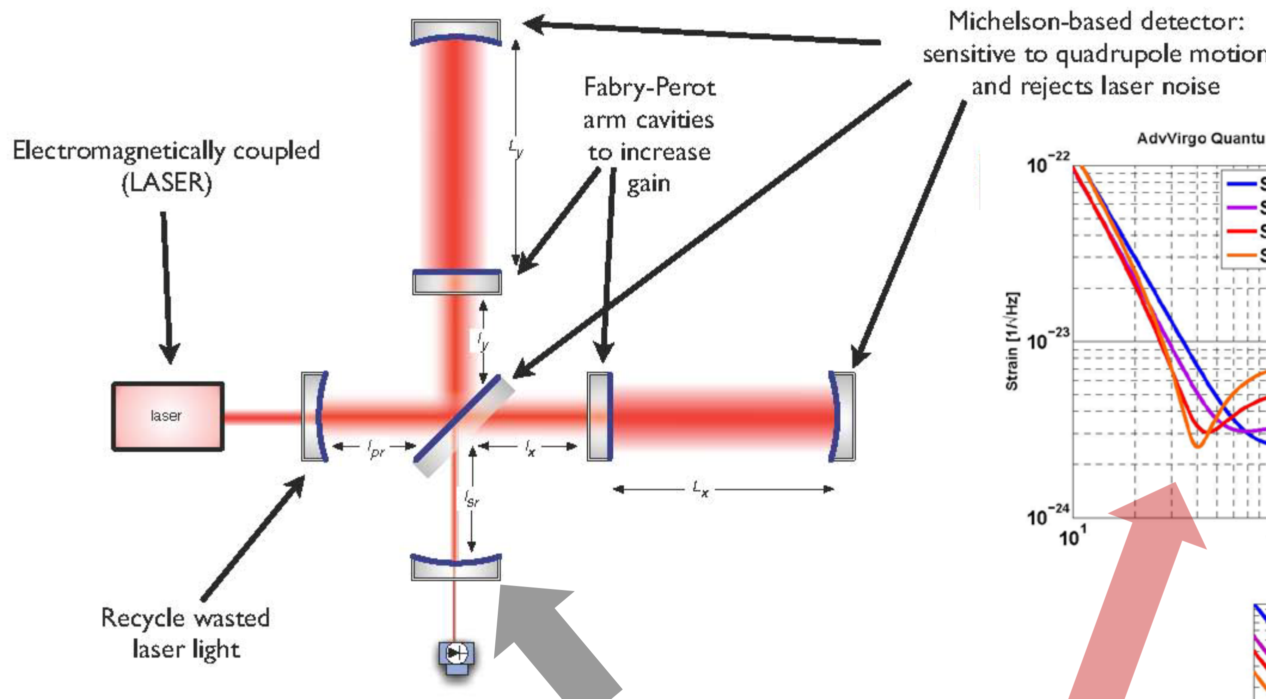
- Avoid degradation of interferometer performance due to thermal lensing
  - Reduce wavefront distortion in recycling cavities
  - Correct mirrors surface deformation
- Thermal compensation
  - Combined action of a CO_2 laser and heating rings
  - CO_2 laser cannot act directly on test masses
  - Project CO_2 laser on silica compensation plates
    - Drawback: additional optics on the main beam

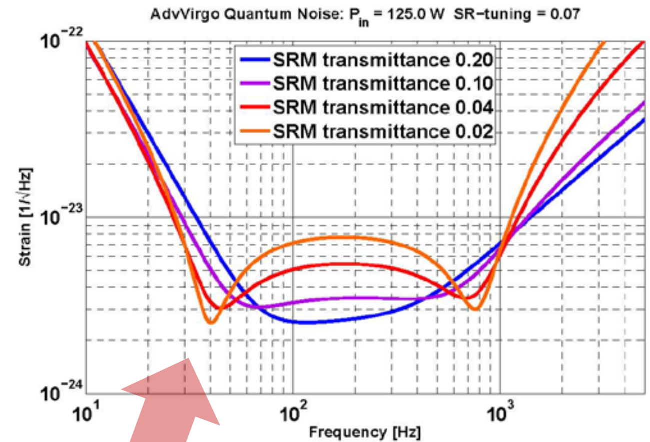
Shielded heating rings will compensate HR surface deformations

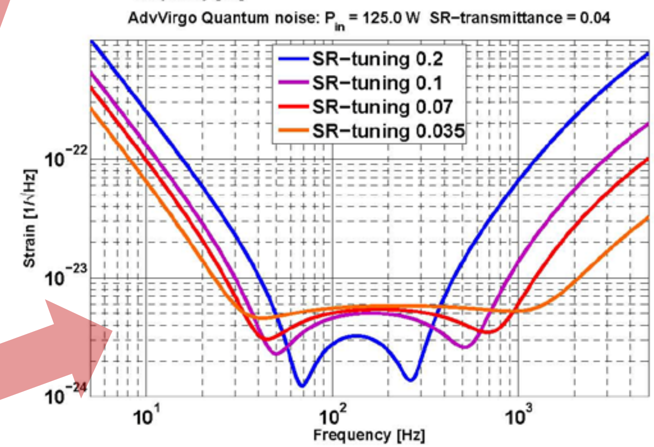


Compensation plates shined with CO_2 laser will correct thermal effects in the power recycling cavity

Signal recycling







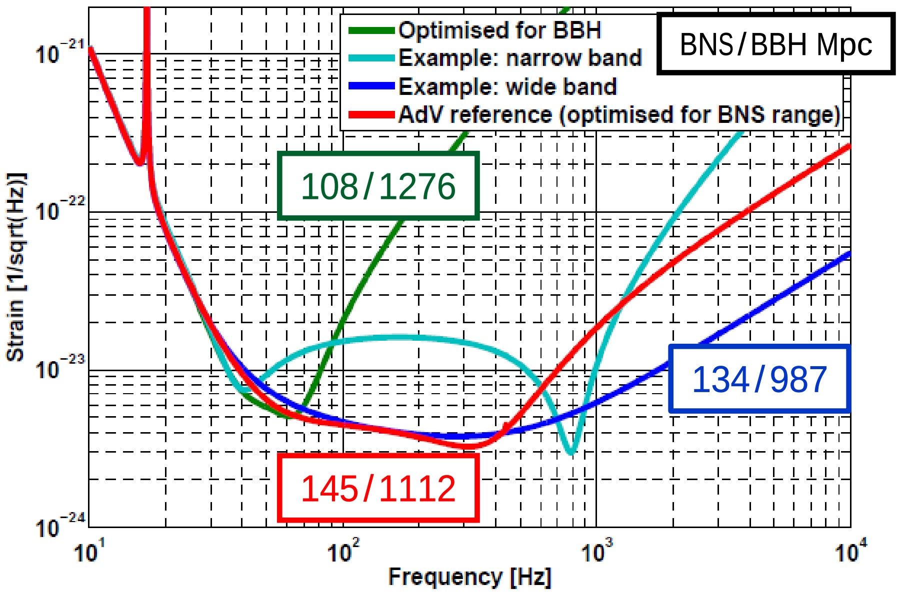
Signal recycling

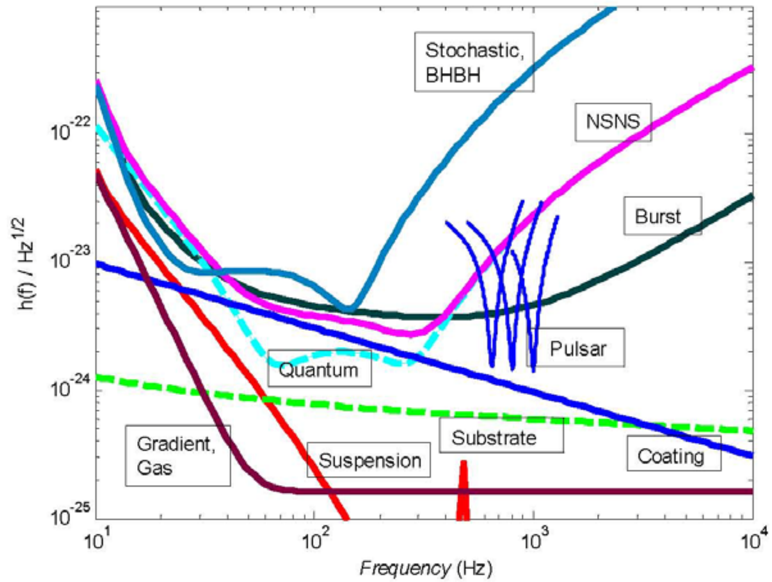
Shape the signal frequency response

SR mirror transmittance ➔ bandwidth

SR mirror tuning ➔ peak sensitivity frequency

Sensitivity tunability

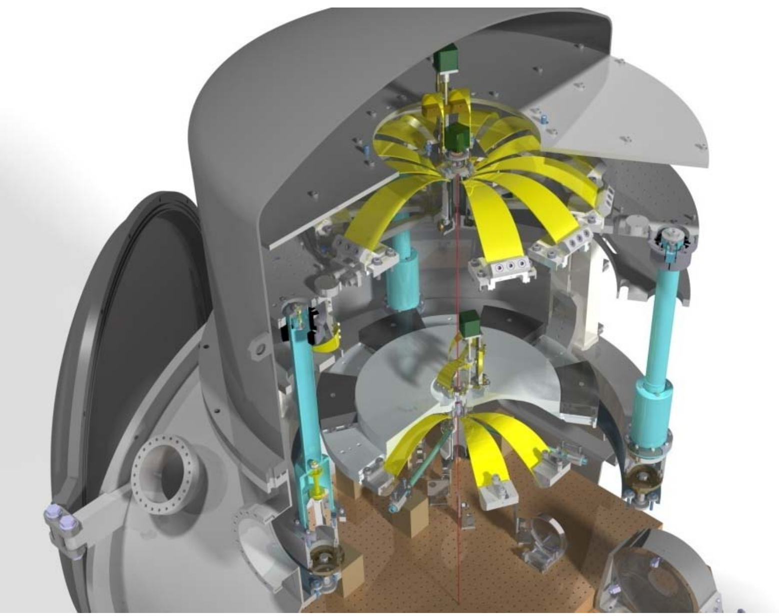


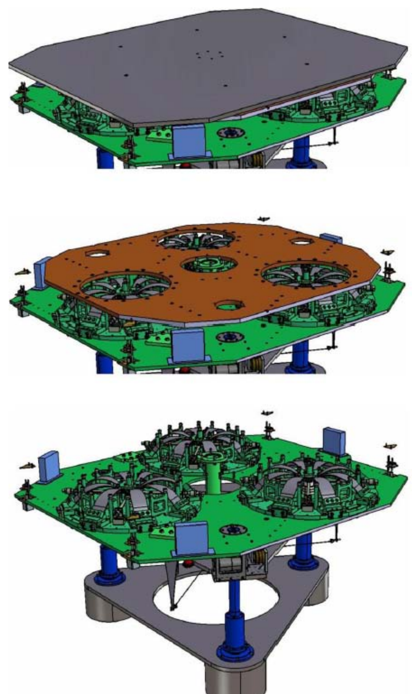


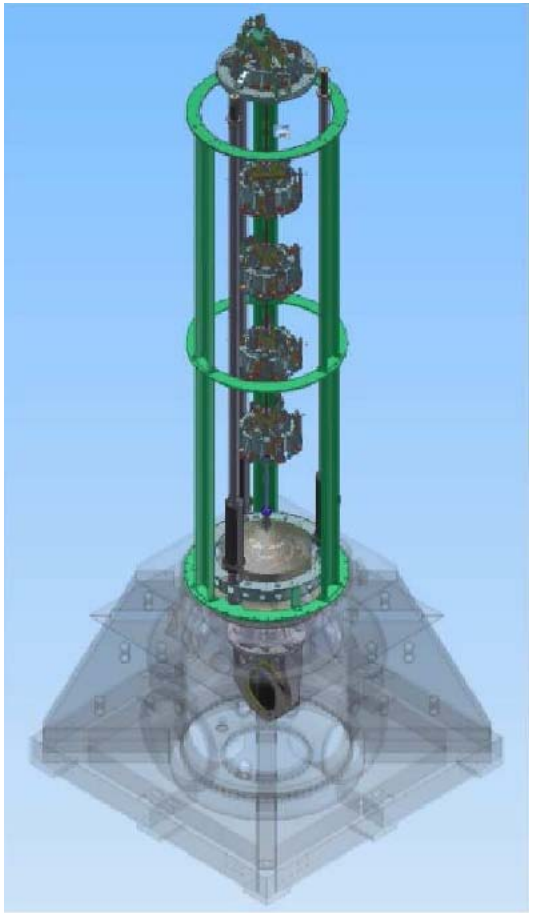
- Some degrees of freedom in the advanced detectors sensitivity curves
  - some contingencies too…
- Can be tuned to detect/study various sources

Seismic isolation

- Isolate optics from ground motion
- Main attenuator already compliant but some upgrades foreseen
- New isolated benches for injection or detection

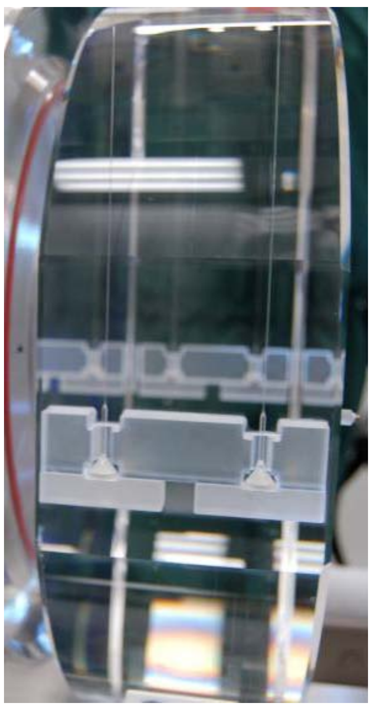


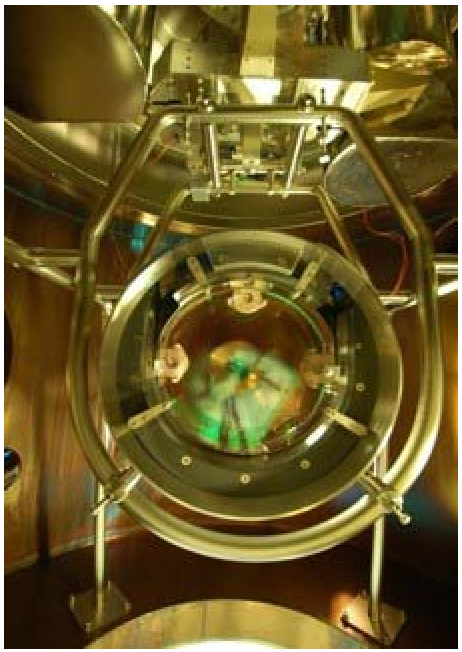


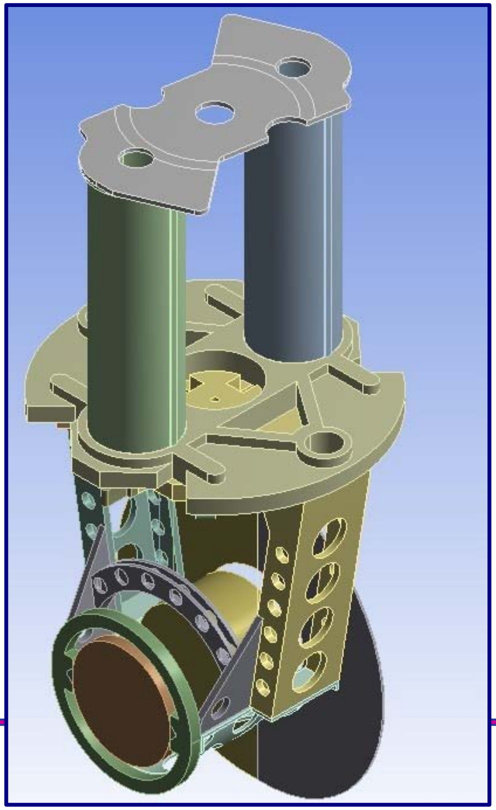


Monolithic suspensions

- Reduce suspension thermal noise
  - Use fused silica fibers to suspend the test masses
- Mature technology implemented in Virgo+
  - But Advanced Virgo payload more complex

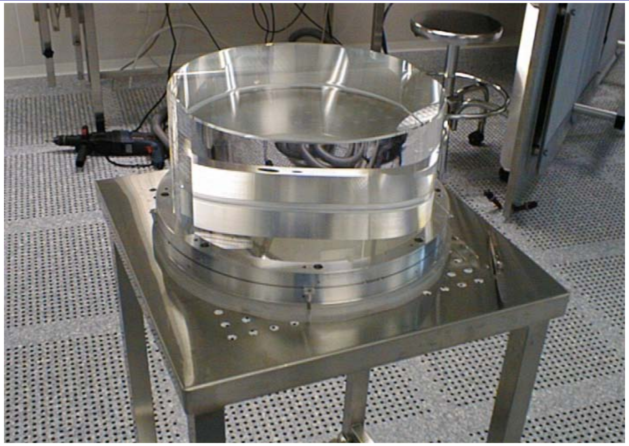


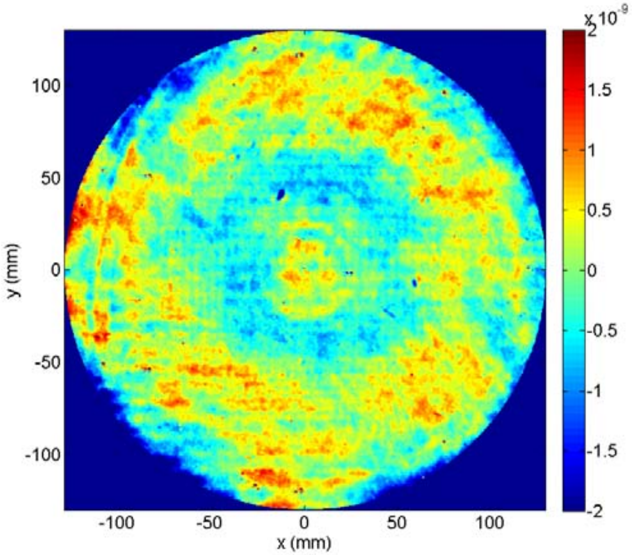




Mirrors

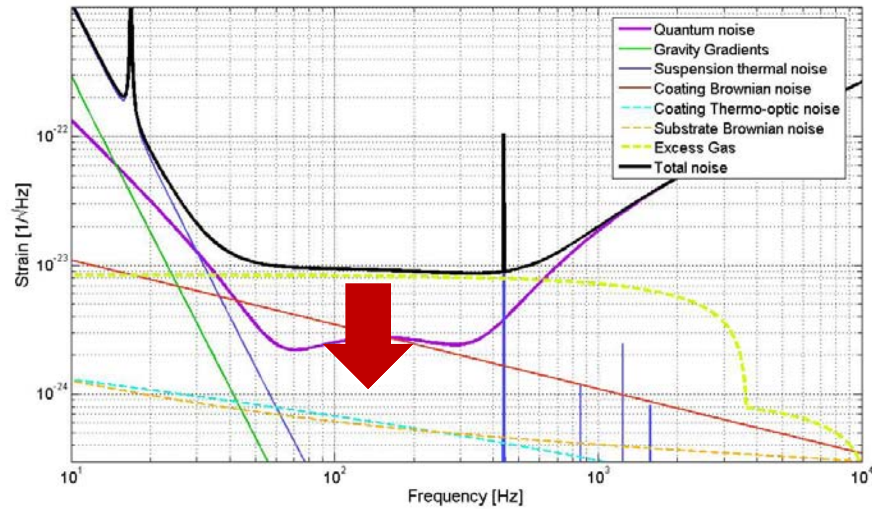
- Main requirements
  - Radiation pressure noise mitigation
  - Thermal noise reduction
  - Scattering losses reduction
- Larger mass
  - 35 cm diameter, 20 cm thick, 42 kg
- Ultra-low absorption fused silica
- Scattering loss reduction
  - Sub-nanometer polishing needed
  - Ion beam polishing or corrective coating
- State of the art low loss coating





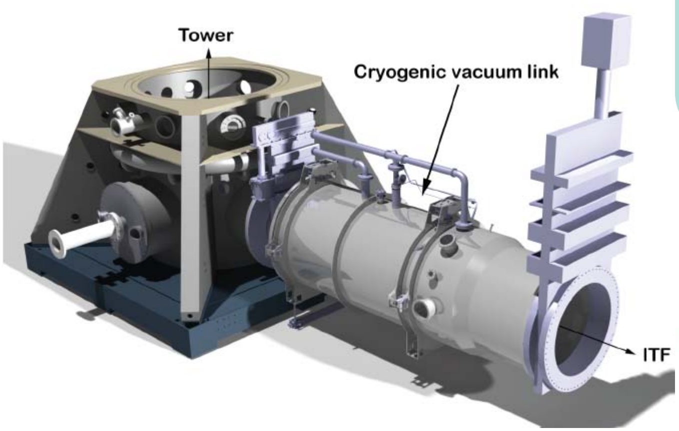
Vacuum

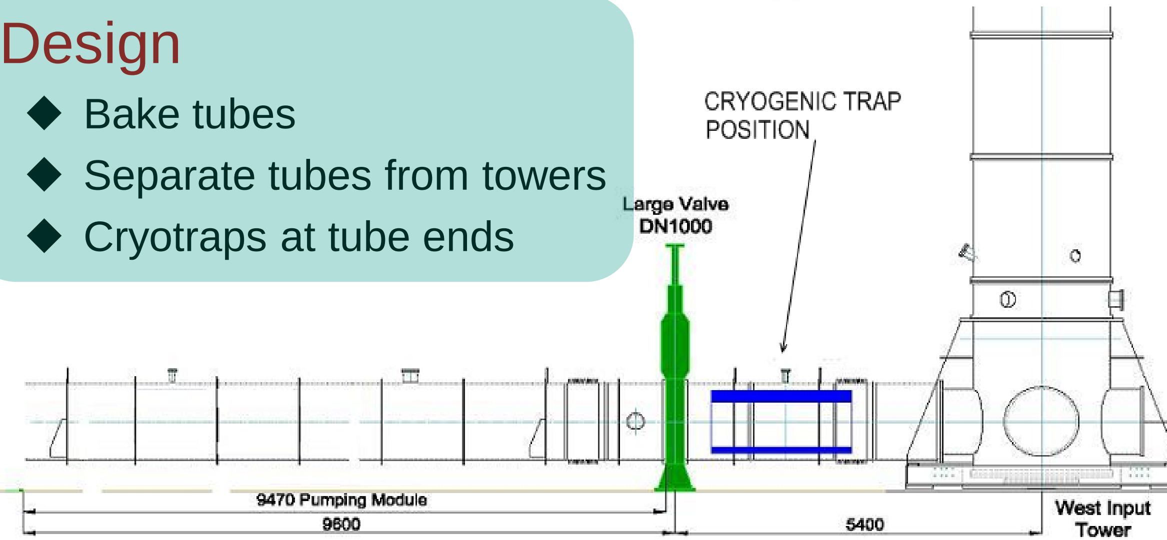
- Goal
  - Reduce noise due to index of refraction fluctuations
- Residual pressure in Virgo tubes
  - Current pressure ~ 10^{-7} mbar
  - /100 reduction required



Design

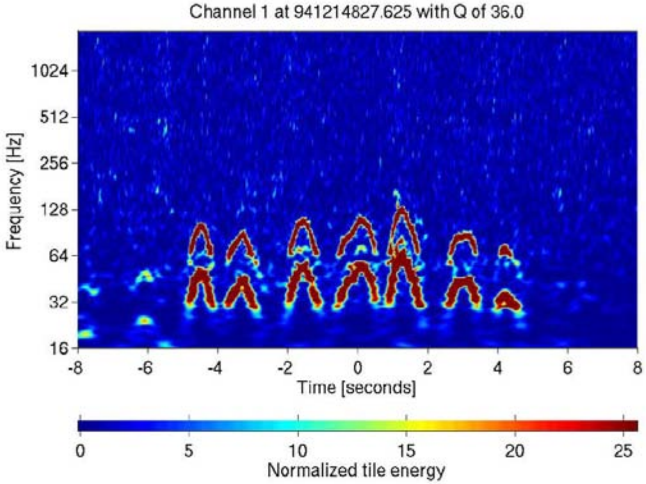
- Bake tubes
- Separate tubes from towers
- Cryotraps at tube ends





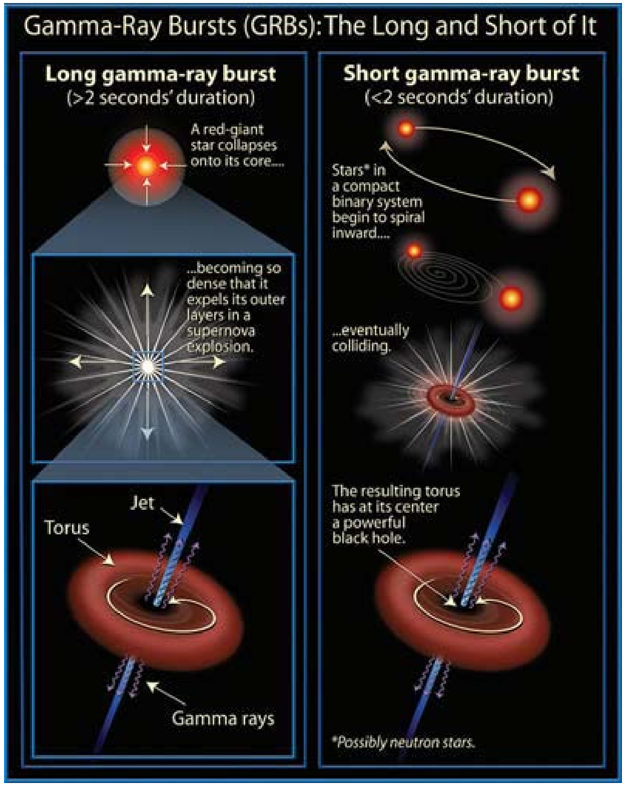
Dealing with scattered light

- Scattered light can couple back to main beam
  - Phase modulated by movement of scattering surface
  - Source of excess noise + non-stationary noise (glitches)
- Trap stray light
  - Baffles, beam dumps…
- Minimize coupling by seismically and acoustically isolating sensitive elements



Toward multi-messenger astronomy

Exploiting all messengers

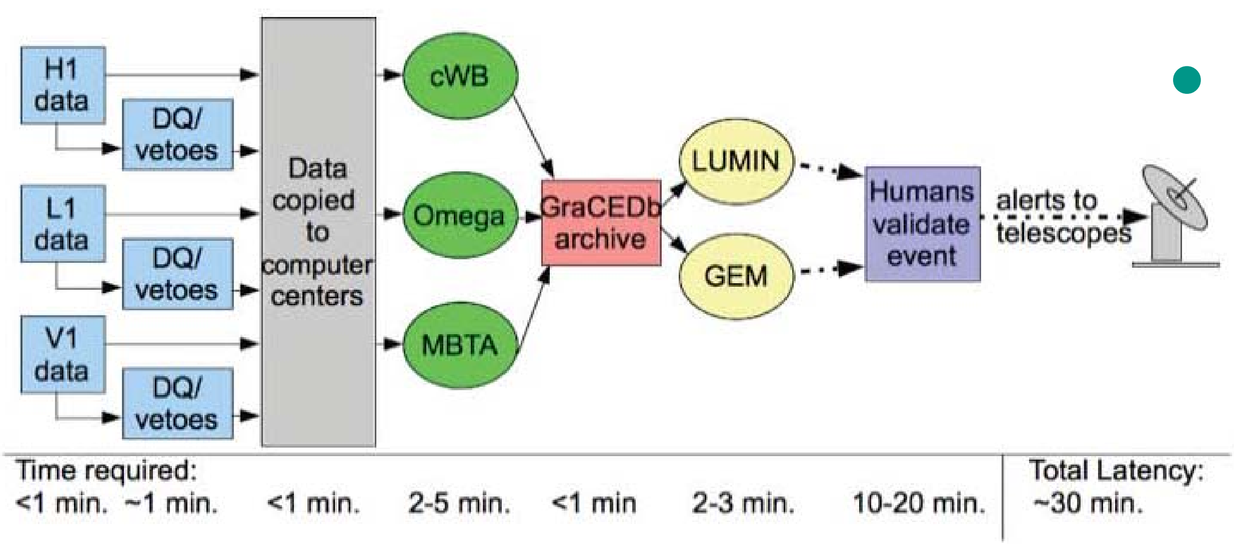


- Emblematic example: gamma ray bursts
  - ◆ Expected gravitational wave sources
    - » Probe dynamics of central engine
  - ◆ High energy neutrinos
    - » Matter – radiation interaction
  - ◆ Burst afterglow
    - » Timescale // wavelength
  - ◆ Isotropic radioactive decay?
- Search for GW associated with GRBs
- Search for GW-HEN coincidences

- Search for electromagnetic counterparts to GW events
  - ◆ Fast follow-up program with partner telescopes / satellites

GW-triggered EM follow-ups

- Key ingredients
  - Low-latency analysis, including reliable estimate of events significance
  - Fast source localization for potentially interesting events
  - Procedures to clear events and send alerts
  - Partners
    - » X-ray, optical, radio in LOOCUP program in 2009-2010



- Challenges
  - Image analysis to identify transients
  - Handling transient false alarm rate
  - Combining GW and EM information

EM follow-up in advanced detector era

- A hot topic for internal discussion right now!
- Continue with MoU model for first detections
  - May issue open alerts later, in routine detection era
- Make sure all relevant partners join the fun
  - From big telescopes/satellites to dedicated, medium-size robotic telescopes
  - Open call will be issued
- Deal with poor sky localization from GW

Network	Sources localized within				Worst Area (deg^2) (SNR>8 per ITF)
	1 deg^2	5 deg^2	10 deg^2	20 deg^2	
HHLV	0.5%	6%	15%	42%	150

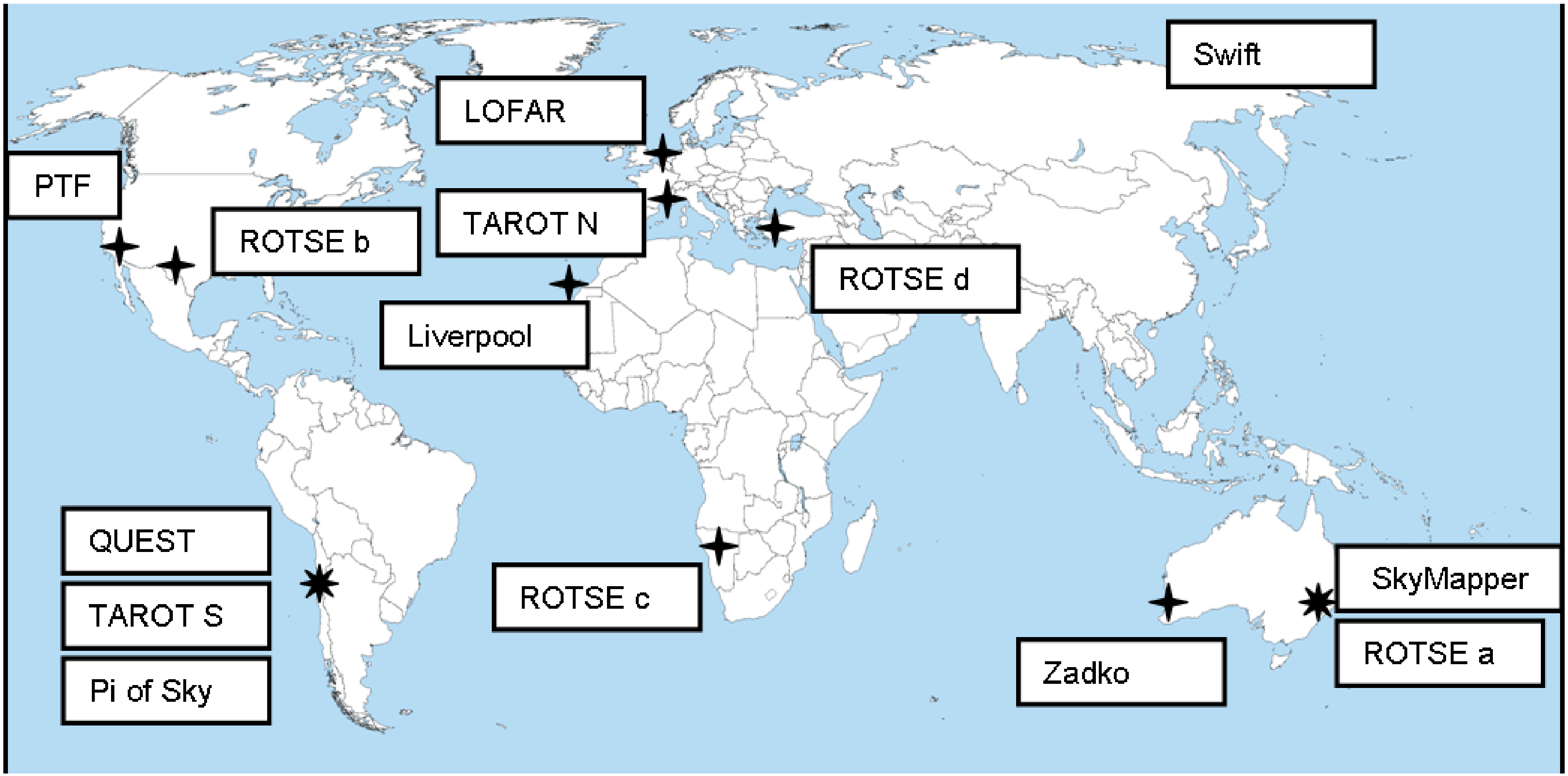
Adapted from Fairhurst arXiv/1010.6192

- Get everyone interested, without raising unrealistic expectations
  - First data in 2015-2016, final sensitivity reached ~2020, unpredictable rate of progress in between

Conclusion

- GW promise a new, powerful tool for fundamental physics, astrophysics, cosmology
- Field & community matured with 1st generation ground-based detectors
- Second generation detectors coming online soon
  - Go through construction, commissioning, observation and… detections!
  - Multi-messenger key ingredient for successful science
  - Prepare the future: 2.5 and 3rd generations…
- LISA: get ready for L2 selection
  - Relying on a successful LISA-Pathfinder
- Keep an eye on pulsar timing arrays!

2009-2010 LOOCUP Program



Virgo : évolution de l'horizon CBC

Virgo ➔ Virgo+

Virgo+ ➔ Virgo+ avec suspensions monolithiques

Correction courbure des miroirs NE et WE

VSR1

VSR2

VSR3

VSR4